Defense Technical Information Center Compilation Part Notice

ADP012779

TITLE: InAs Nanoscale Islands on Si Surface: A New Type of Quantum Dots

DISTRIBUTION: Approved for public release, distribution unlimited
Availability: Hard copy only.

This paper is part of the following report:

TITLE: Nanostructures: Physics and Technology International Symposium [6th] held in St. Petersburg, Russia on June 22-26, 1998 Proceedings

To order the complete compilation report, use: ADA406591

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP012712 thru ADP012852

Ioffe Institute
6th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 22–26, 1998.

InAs nanoscale islands on Si surface: a new type of quantum dots

G. E. Cirlin†, V. G. Dubrovskii†, V. N. Petrov†, N. K. Polyakov†,
N. P. Korneeva†, V. N. Demidov†, A. O. Golubok†, S. A. Masalov†,
D. V. Kurochkin†, O. M. Gorbenko†, N. I. Komyak†,
N. N. Ledentsov‡, Zh. I. Alferov‡ and D. Bimberg§

† Institute for Analytical Instrumentation RAS, St. Petersburg, Russia
‡ Ioffe Physico-Technical Institute RAS, St. Petersburg, Russia
§ Institut für Festköperphysik, Technische Universität Berlin, Germany

Abstract. We study epitaxial growth of InAs onSi(100) surface using molecular beam epitaxy. We found that at moderate arsenic fluxes and substarte tempeartures (470 °C) the growth proceeds in Stranski–Krastanow growth mode with formation of mesoscopic dislocated clusters on top of the two-dimensional periodically-corrugated InAs wetting layer. At lower temperatures (250 °C) a dense array of self-organized nanoscale InAs quantum dots with good size and shape uniformity is formed.

Introduction

Silicon is a key material in modern semicondiuctor technology. Such advantages of silicon as: high heat conductivity, high stiffness, availability of stable oxide and developed technology of cheep large-area dislocation free substrates make this material advantageous for numerous applications in microelectronics. As opposite, the indirect bandgap nature of Si makes it hardly available for applications in optoelectronics, as the probability of radiative recombination of nonequilibrium is very low. With the example of III–V materials, however, it is well known; that the luminescence efficiency of indirect gap material can be dramatically improved by placing of thin layers (quantum well) of narrow gap direct gap materials inside the indirect gap matrix (e.g. GaAs layers in AlAs). Nonequilibrium carriers are trapped in direct gap regions and the luminescence efficiency can be very high, even the relative total thickness of the narrow gap material is small. However, the quantum well (QW) needs to be thick enough not to let the size quantization effect to increase the bandgap of the direct gap insertion above the bandgap of the indirect gap matrix. As the lattice constants for narrow gap III–V compounds and Si differ significantly, formation of thick-enough narrow gap III–V layers without creation of dislocations is not possible. On the other hand, again, from III–V heteroepitaxial growth experience, it is well known that the effect of spontaneous formation of nanoscale strained islands in lattice mismatched epitaxy can be applied for fabrication of coherent quantum dots (QDs) with small bandgap energies and, simultaneously, high luminescence efficiencies. We proposed to use the similar approach for fabrication of coherent narrow gap III–V quantum dots to realize high luminescence efficiency in silicon to develop a principally new approach for integration of opto- and microelectronic devices using the same silicon host material [1]. The possibility of fabrication of III–V quantum dots on silicon surface using this approach; however, is not evident.

The heteroepitaxial InAs-Si system is characterised by a very high lattice mismatch (approximately 10 percents). Here we show that under specific growth conditions InAs QDs, satisfying the necessary size requirements (essentially 3D with lateral size above 12 nm) can be fabricated on Si (100) surface.

1 Experimental

The growth experiments were carried out using EP1203 MBE machine (Russia) on exactly oriented Si(100) substrates, either semi-insulaing or having n-type conductivity. The Si(100) surface preparation is performed in a way similar to described in [2]. The substrates were mounted on a Mo substrate holder using an indium melt. Thermal desorption of the silicon native oxide layer was performed at substrate temperature of 820 °C in 15 min. After this procedure a well resolved (2×1) surface reconstruction typical for cleaved Si(100) surface has been observed. After this the substrate temperature was smoothly decreased to the desired experimental value and the InAs deposition was initiated in a conventional MBE mode. The InAs deposition rate was 0.1 monolayers per second. After the deposition of the desired average thickness of the InAs on Si surface, the sample was immediately quenched to the room temperature and removed from the growth chamber. Pieces for STM studies were then covered with silicon vacuum oil immediately after exposure to atmosphere.

For *in situ* control of the surface morphology before and during growth, calibration of the growth rate and the III–V flux ratio, reflection high energy electron diffraction (RHEED) system composed of high sensitivity video camera, video tape recorder and PC computer interconnected via specially-designed interface has been used [3]. Surface morphology was also studied *ex situ* in different scanning probe microscopy setups. For scanning tunnelling microscopy (STM), we used the samples covered with oil to prevent the surface oxide layer formation affecting reliability of STM measurements. The atomic force microscopy (AFM) measurements have been carried out in ambient pressure using uncovered samples.

2 Results and discussion

In case of the InAs-Si(100) deposition at moderate arsenic fluxe ($1 \cdot 10^{-6}$ torr) and substrate temperature of 470 °C, the RHEED pattern remained streaky up to deposition of 60 MLs of InAs. A transition from (2×1) to (3×1) surface reconstruction has been observed. STM images of the surface of the sample grown in these conditions are presented in Fig. 1 and Fig. 2 (n-type substrate). One can see that mesoscopic InAs clusters having a 400 nm lateral size (Fig. 1) are clearly revealed in the image. In between of the clusters one can resolve weak corrugation of the reamaining InAs wetting layer with a characteristic period of about 25 nm (see Fig. 2). AFM measurements of the sample grown in similar conditions, but on semiinsulating substrate revealed similar morphology. The results for this temperature range can be interpreted as follows, after formation of InAs coherent wetting layer on Si (100) surface, as detected by the change in the surface reconstruction, most of the InAs deposited concentrates in well-separated mesoscopic dislocated clusters. As the most of the surface remains flat, the RHEED measurements denmonstarte 2D diffraction pattern.

Very different growth scenario occurs when the substrate temperature is reduced to 250 °C. In this case RHEED pattern was converted from streaky to spotty after 5.5

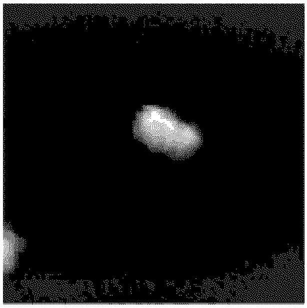

Fig. 1. STM image of the InAs huge clusters on the Si surface (60 ML of InAs, substrate temperature 470 °C). Scan area is 2000 nm × 2000 nm. Sides of the image are parallel to [011] and [0$\bar{1}$1] directions.

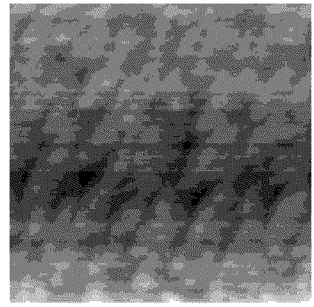

Fig. 2. STM image of the InAs corrugated surface in between the huge islands (60 ML of InAs, substrate temperature 470 °C). Scan area is 400 nm × 400 nm. Sides of the image are parallel to [011] and [0$\bar{1}$1] directions.

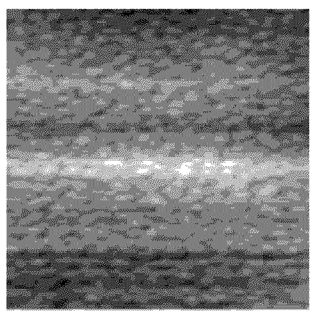

Fig. 3. STM image of the InAs nanoislands on Si surface (6 ML of InAs, substrate temperature 250 °C). Scan area is 400 nm × 400 nm. Sides of the image are parallel to [011] and [0$\bar{1}$1] directions.

monolayers (MLs) of InAs ware deposited. This transition indicates formation of three-dimensional islands. No further InAs deposition was performed in this case. STM image of the surface arrangement formed at 250 °C is shown in Fig. 3. On can conclude that InAs forms a remarkably dense array of uniform nanoscale islands (quantum dots) with good size and shape uniformity. For higher magnifications a well resolved crystalline shape of anysotropic QDs can be revealed. Cross-sectional analysis of the image gives the lateral size of the QD about 12 nm in one directions and 20 nm in the other, while the height of the QD is about 4 nm. The surface density of QDs is $5 \cdot 10^{11}$ cm^{-2}.

Considerable difference between surface morphology at 470 °C and 250 °C can be explained by a change in surface energetics with change in substrate temperature, as reported also for InAs growth on GasAs, but for change in arsenic flux. At low temperatures the total surface energy of the island is smaller than that of the underlying wetting layer due to the strain-induced renormalization of the surface energy [4]. At high temperatures, the total surface energy of the island is higher than that of the underlying wetting layer making island making ripening process energetically favourable. We note that at similar growth conditions no ripening is revealed for InAs islands formed on InAs wetting layer on GaAs(100) surface. Thus a higher diffusion coefficient for In adatoms at higher substrate temperature does not necessarily leads to formation of mesoscopic clusters, and the energy benefit for ripening must be present as pointed in [4]. The Ostwald ripening process is kinetically controlled finally resulting in formation of large dislocated islands. Resulting surface topography thus contains mesoscopic islands and a corrugated wetting layer between them. Such a behaviour is typical for many heterosystems undergoing the Ostwald ripening and has been theoretically described in [5]. At lower temperatures an equilibrium array of islands is formed similar to the InAs-GaAs(100) growth [6], however in a much wider temperature range. Change from one mechanism to another may be related to a change in surface reconstruction either of the wetting layer or of the facets of the islands.

The characteristic time for formation of InAs nanoislands when crytical thickness (5.5 MLs) is of the order of 1 s for growth rate of 0.1 ML/s. Such a sharp 2D–3D transition has been previously observed in several semiconductor heteroepitaxial systems, in particular InAs/GaAs [6], Ge/Si [7] and theoretically considered using microscopic kinetic approach in [8].

To conclude, we proposed and denmonstrated a possibility to form InAs quantum dots of requested for optoelectronic applications size on Si surface using molecular beam epitaxy. Self organized formation of dense arrays of nanoislands uniform in size and in shape is demonstrated. The next step will be to cover InAs QDs with silicon and investigate their optical properties.

Acknowledgements

Authors wish to thank Dr. A. S. Berdnikov for the help in preparing the manuscript. This work was partially supported by INTAS Grant No. 96-0242 and Scientific Program "Physics of solid state nanostructures".

References

[1] N. N. Ledentsov, in: *Proc. 23th Int. Conf. Phys. Semiconductors* Berlin, 1996, Ed. by M. Scheffler and R. Zimmermann (World Scientific, Singapoure, 1996), v. 1, p. 19.
[2] A. Ishisaka, Y. Shiraki, *J. Electrochem. Soc.* **133** 666 (1986).
[3] G. E. Cirlin, N. P. Korneeva, D. N. Demidov, N. K. Polyakov, V. N. Petrov, N. N. Ledentsov. *Semiconductors* **31** 1057 (1997).
[4] V. A. Shchukin, N. N. Ledentsov, M. Grundmann, P. S. Kop'ev, D. Bimberg. *Phys. Rev. Lett.* **75** 2968 (1995).
[5] S. A. Kukushkin, A. V. Osipov. *Prog. Surf. Sci.* **51** 1 (1996).
[6] G. E. Cirlin, G. M. Guryanov, A. O. Golubok, S. Ya. Tipissev, N. N. Ledentsov, P. S. Kop'ev, M. Grundmann, D. Bimberg. *Appl. Phys. Lett.* **67** 97 (1995).
[7] J. Zhu, K. Brunner, G. Abstreiter. *Appl. Phys. Lett.* **72** 424 (1998).
[8] V. G. Dubrovskii, G. E. Cirlin, D. A. Bauman, V. V. Kozachek, V. V. Mareev. *Tech. Phys. Lett.* (submitted).